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April 16, 2003
Contract NRC–02–02–012
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U.S. Nuclear Regulatory Commission
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Subject: Intermediate Milestone 20.06002.01.131.320, Evaluation of Alternative Concepts for Saturated Zone Flow

Dear Dr. Arlt:

This letter transmits Intermediate Milestone 20.06002.01.131.320, Evaluation of Alternative Concepts for Saturated Zone Flow. This report documents the use of the CNWRA three-dimensional groundwater flow model to evaluate DOE groundwater flow simulations for the Yucca Mountain region. Specifically, the effects of recharge rates and boundary conditions on calculations of saturated zone flow paths, groundwater travel times, and potential magnitudes of water table rise during future climate conditions. Modeling case studies show that the inclusion of relatively minor amounts of recharge over the potential repository area can produce a substantial decrease in saturated zone groundwater travel times from Yucca Mountain. In the case studies presented, inclusion of 5 mm/yr recharge above the repository area resulted in an order of magnitude decrease in average groundwater travel times to the regulatory compliance boundary, compared to the case where no recharge was considered in the repository area. Modeling studies developed in this report also suggest that further increases in recharge rates and a water table rise that may accompany a future wetter climate, combined with the addition of recharge in the Fortymile Wash area did not substantially affect calculated flow paths or groundwater travel times. An evaluation of the potential magnitude of water table rise during future climate conditions, constrained by observed evaporite deposits, suggests that the potential magnitude of future water table rise beneath the proposed repository area could be in the range of 50–150 m; this magnitude is consistent with the 120 m water table rise assumed in U.S. Department of Energy performance assessments.

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If you have any questions about this deliverable, please contact me (210.522.5540) or Mr. James Winterle (210.522.5249).

Sincerely yours,

English C. Pearcy
Manager, Geohydrology and Geochemistry

ECP: ar
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EVALUATION OF ALTERNATIVE CONCEPTS FOR SATURATED ZONE FLOW: EFFECTS OF RECHARGE AND WATER TABLE RISE ON FLOW PATHS AND TRAVEL TIMES AT YUCCA MOUNTAIN

Prepared for

U.S. Nuclear Regulatory Commission
Contract NRC–02–02–012

Prepared by

James R. Winterle

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April 2003

ABSTRACT

The Center for Nuclear Waste Regulatory Analyses three-dimensional groundwater flow model was used to evaluate the effects of conceptual model uncertainty regarding recharge and boundary conditions on calculations of saturated zone flow paths, groundwater travel times, and potential magnitudes of water table rise during future climate conditions. Four modeling case studies presented in this report indicate that consideration of recharge over the potential repository area can result in an order of magnitude decrease in calculated groundwater travel times for the effective porosities assumed for these modeling studies. Increased recharge in the model area north of Yucca Mountain and water table rise that may accompany a future wetter climate and the addition of recharge in the Fortymile Wash area did not substantially affect flow path or travel time calculations in the case studies presented in this report. However, the effects of these processes should be evaluated for alternative hydrogeologic interpretations. The Case 4 modeling study presented here provides a reasonable basecase scenario for the abstraction of saturated zone flow and transport in performance assessments using the Total-system Performance Assessment code.

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–02–012. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The author wish to thank G. Walter for thorough technical review and useful insights, C. Cudd and B. Long for editorial expertise, and B. Sagar for programmatic review. The administrative and format support provided by A. Ramos is greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

No original data were generated from the analyses presented in this report. The Grid and MODFLOW–96 (Harbaugh and McDonald, 1996) and MODPATH (Pollack, 1994) modules of the Groundwater Modeling System (GMS) Version 3.1 (Environmental Modeling Research Laboratory, 1999) were used to construct and execute the groundwater flow models presented in this report. The GMS interface and MODFLOW groundwater modeling codes have been validated in accordance with CNWRA technical operating procedure TOP–18. Documentation of the GMS modules and demonstration versions of the code can be found at the EMS-i Internet site: http://www.ems-i.com. CNWRA presently maintains two user licenses for the GMS Version 3.1, which contain all codes and documentation. All input and output files for the groundwater flow models presented in this report are archived as model version S6a and documented in CNWRA Scientific Notebook 480E.

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1 INTRODUCTION

The Center for Nuclear Waste Regulatory Analyses (CNWRA) developed a three-dimensional, site-scale, saturated-zone flow model for the Yucca Mountain region. This model provides the U.S. Nuclear Regulatory Commission (NRC) and CNWRA staff with a tool to evaluate the effects of uncertainties in parameter and conceptual models on estimated flow paths and groundwater fluxes at Yucca Mountain, the site of a proposed high-level waste repository. Such modeling analyses can provide the NRC staff with an improved vantage point from which to assess the adequacy of the U.S. Department of Energy (DOE) site-scale flow model (CRWMS M&O, 2000a) used to support performance assessments of the proposed repository.

In this report, the CNWRA flow model is used to evaluate the effects of different model conceptualizations of areal recharge and regional water table elevation on modeled flow paths from Yucca Mountain and groundwater travel times to the 18-km [11-mi] regulatory compliance boundary specified in 10 CFR Part 63.

2 MODEL DESCRIPTION

The CNWRA saturated zone flow model for Yucca Mountain was developed by Winterle, et al. (2002) using the Groundwater Modeling System (GMS) Version 3.1 for model grid development and for execution of the MODFLOW–96 groundwater flow model and the MODPATH particle-tracking algorithm. The computational grid covers a 28.5 × 41.4-km [17.7 × 25.7-mi] area surrounding Yucca Mountain as shown in Figure 2-1. The model domain extends vertically from 1,200 m [3,940 ft] above mean sea level to 1,500 m [4,920 ft] below mean sea level. There are 30 horizontal layers in the numerical grid, which vary in thickness from 50 m [164 ft] to 200 m [656 ft], with the thinnest grid layers assigned at and below the water table where flow paths from Yucca Mountain might occur. Each of the 30 layers is uniformly divided into 300-m [900-ft or 1.5 furlong] square horizontal grid blocks for a total of 393,300 computational cells. This grid discretization was the result of a tradeoff between being fine enough to define hydrostratigraphic and structural features and being coarse enough to minimize computation time. Model grid cells above the computed water table elevation are rendered inactive in the flow simulations.

An interpretation of the water table surface (Figure 2-1) was used to assign constant head boundary conditions to the vertical sides of the model. Water table elevations in the Yucca Mountain area were summarized by Hill, et al. (2002). Hydraulic heads at the vertical boundaries were assumed constant with depth. Although hydraulic heads do vary with depth, the model boundaries were selected far enough from potential flow paths of interest that the effects of this assumption are mitigated. The bottom of the model is treated as a no-flow boundary, and it is assumed that the model domain extends deep enough that the effects of this assumption are mitigated for groundwater transport pathways near the top of the model. These boundary assumptions were justified by the ability to obtain a reasonably good model calibration.

The model explicitly includes 19 hydrostratigraphic and structural material types based on the 18 features identified in the CNWRA independent hydrogeologic framework model for the Amargosa region (Sims, et al., 1999). Note that the caldera zone from the framework model is split into two material types for the flow model, hence, the difference in the number of features. Each model grid cell is assigned a hydrostratigraphic or structural material type, and each

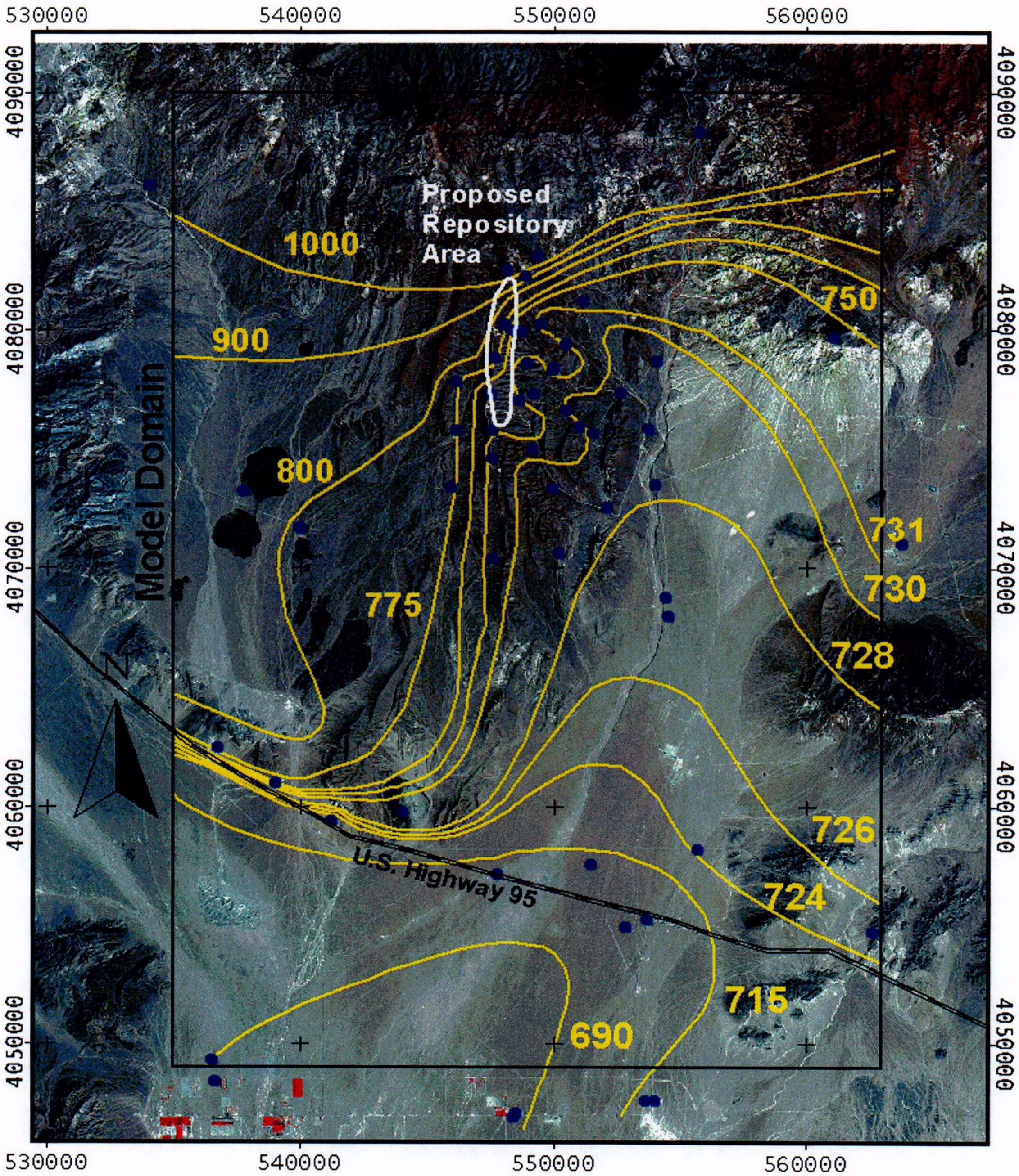

Figure 2-1. Satellite Map of the Yucca Mountain Region Showing Model Domain, Interpreted Water Table Elevation Contour Lines (Units Are Meters Above Mean Sea Level for Conversion to Feet, Use 1 m = 3.281 ft), and Locations of Observation Wells Used to Interpret the Water Table (Blue Circles). Map Coordinates are UTM NAD–27 Meters.

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material type is assigned a constant, isotropic hydraulic conductivity value. Descriptions of material types and calibrated hydraulic conductivity values are listed in Table 2-1. The current model contains a few minor changes to the material types assigned in the earlier model grid of Winterle, et al. (2002). For example, the model grid cells representing the northern end of the Solitario Canyon fault were moved farther west to be consistent with mapped locations of this fault; model cells representing caldera-altered volcanic tuff were extended farther south to reduce model calibration error. Additional discussion of the effects of structural and hydrostratigraphic features on model calibration is contained in the results section of this report.

The current site-scale flow model contains another important improvement from the earlier model of Winterle, et al. (2002). The earlier model used the confined aquifer solution option of the MODFLOW code; this option did not permit model cells to dry out or rewet and, thus, potential effects of changes in the water table elevation could not be considered for alternative model conceptualizations. The current model uses the confined/unconfined option of the MODFLOW Block Centered Flow package for the top seven layers of the numerical grid. This algorithm makes use of an unconfined-flow solution when model cells coincide with the water table and a confined-flow solution for cells entirely below the water table. Model cells entirely above the interpreted water table are assumed dry and treated as inactive.

The MODFLOW Recharge package is used to include areal sources of groundwater influx to the top surface of the model. The recharge algorithm allows the user to specify the areas where recharge occurs, and the code automatically assigns the specified recharge rate as an influx to the top face of the uppermost active model cell beneath the recharge area. Thus, if a model cell is calculated to be dry (i.e., unsaturated) during a simulation, the recharge flux is simply reassigned to the top face of the next lower cell.

Four models were developed to evaluate the potential effects of areal recharge and regional water table rise on estimated flow paths and groundwater travel times. These models, referred to as Case 1 through Case 4, are described next:

<u>Case 1</u>: This model was used for the trial-and-error calibration of hydraulic conductivity values assigned to the material types, which were then used for the remaining three cases. The descriptions of the model material types and the calibrated hydraulic conductivity values for the Case 1 model are listed in Table 2-1. A constant recharge rate of 10 mm/yr [0.4 in/yr] was applied to the model area north of Yucca Mountain, indicated by the red shaded areas in Figure 2–2(a).

<u>Case 2</u>: This model is identical to the Case 1 model with the exception that a recharge rate of 5 mm/yr [0.2 in/yr] is applied to the area surrounding the footprint of the proposed repository at Yucca Mountain, as indicated by the yellow shaded area in Figure 2-2(a).

<u>Case 3</u>: The Case 3 model assesses the potential effects of increased infiltration rates and a regional water table rise that might occur following a shift to wetter climate conditions. For this model, recharge rates were doubled from the Case 2 model and constant-head values at the model side boundaries were increased by 5 percent as explained in Section 3.3.

<u>Case 4</u>: This model is identical to Case 3, except for the addition of a new recharge area along the incised channel of Fortymile Wash and the lower reaches of two of its tributaries. For this

Table 2-1. Material Types and Assigned Model Properties			
Material Type	**Description**	**Hydraulic Conductivity [m/d]**	**Porosity***
PZ	Deep Paleozoic aquifer system	0.05	0.01
UVA	Uppermost volcanic aquifer	0.5	**0.001**
UVC	Upper volcanic confining unit	0.15	**0.1**
LVA	Lower volcanic aquifer	0.15	**0.001**
LVC	Lower volcanic confining unit	0.0002	0.1
Alluv	Valley-Fill alluvium	3.0	**0.1**
FMW	Fortymile Wash fault zone	5.0	**0.001**
BR–PBC	Bow Ridge–Paintbrush Canyon fault zone	4.0	**0.001**
Cald-pz	Caldera zone: altered Paleozoic rocks	0.001	0.01
Cald-vr	Caldera zone: altered volcanic rocks	0.0003	**0.01**
SC-IR	Solitario Canyon–Iron Ridge fault zone	0.0005	0.01
SC-west	Western splay of Solitario Canyon fault zone	0.0005	0.01
CF	Crater Flat fault zone	5.0×10^{-5}	0.01
VH1	VH–1 fault zone	5.0×10^{-5}	0.01
BM	Bare Mountain fault zone	0.05	0.01
H95	Highway 95 fault zone	0.005	0.01
Grav1	Gravity fault zone #1	0.001	0.01
Grav2	Gravity fault zone #2	0.05	0.01
CA	Central Amargosa fault zone	0.5	0.01

*Porosity values reflect order-of-magnitude estimates. Values in boldface reflect hydrostratigraphic units that occur along potential flow paths from Yucca Mountain.

model case, a recharge rate of 200 mm/yr [8 in/yr] is applied to the model area shaded in red in Figure 2-2(b).

MODPATH was used to project groundwater flow trajectories and travel times from 80 points distributed at the water table beneath the proposed repository footprint area. Because the MODPATH input is groundwater flux, not velocity, it is necessary to assign an effective porosity

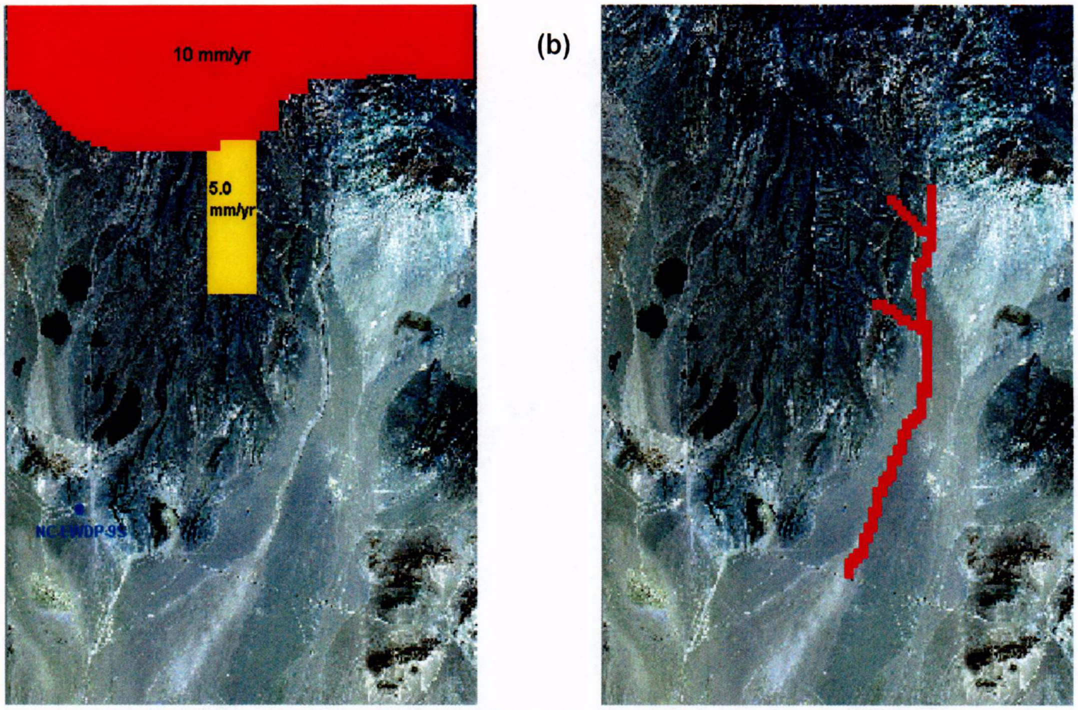

Figure 2-2. Satellite Images of Model Domain Showing (a) Areas of Applied Recharge in Northern Model Area (Red), Yucca Mountain Area (Yellow), and Location of Well NC–EWDP–9S; (b) Area of Recharge (Red) in Fortymile Wash Applied in Case 4 Model. Scale of Model Domain Is Shown in Figure 2-1.

value to each model cell to obtain particle travel time estimates. The porosity values assigned to all model cases are listed in Table 2-1. Values of 0.001 were assigned for welded tuffs where flow occurs mainly in fractures, and 0.1 was assigned for alluvium and nonwelded tuffs where matrix flow may dominate. A value of 0.01 was assigned to the narrow fault zones and the Caldera-altered zones; this intermediate value was chosen arbitrarily because no data on fault zone porosity are available. Considerable uncertainty exists regarding the effective flow porosities of the hydrostratigraphic features. Hence, travel time calculations are presented only for comparison of the alternative conceptual models and should not be regarded with high confidence as predictions of actual groundwater travel times. The assigned porosity values only enter into the travel time calculations for those cells through which the particles pass during the MODPATH simulation. The flow porosity values that occur along flow trajectories from Yucca Mountain are identified in boldface type in Table 2-1.

3 MODEL RESULTS AND DISCUSSION

Steady-state solutions were obtained for each of the four model cases. MODPATH simulations were then used to obtain flow trajectories and total travel times for 80 particles flowing from the water table beneath the proposed repository to the 18-km [11-mi] compliance boundary. Individual results for the four model cases are discussed separately in the following sections.

3.1 Case 1 Model

The Case 1 model represents present-day water table elevations and assumes no recharge in the area of the proposed repository. Most structural and stratigraphic material types used in the model can be seen in the horizontal cross section of model layer 7, shown in Figure 3-1. Figure 3-1 also shows calculated hydraulic head contour lines resulting from the steady-state model calibration using the hydraulic conductivity values listed in Table 2-1. These contour lines illustrate the effects of various hydrostratigraphic and structural features on the modeled hydraulic gradient. It can be seen, for example, that the Solitario Canyon fault (SC–IR) and the caldera-altered volcanic tuff (Caldera_VR) are important for reproducing the large hydraulic gradients observed in the north-central model areas.

Similarly, the vertical cross section through the center of the model domain, shown in Figure 3-2, reveals the importance of the lower volcanic confining unit for reproducing the observed upward hydraulic gradient between the Paleozoic aquifer and the lower volcanic aquifer (represented by LVA, BR–PBC, and FMW units). The calculated hydraulic head at the location of Well UE–25 p#1 is 750.5 m [2,462 ft], which compares favorably to the reported head of 752 m [2,467 ft] (CRWMS M&O, 2000a). Well UE–25 p#1 provides an important calibration point because it is the only well in the central model region to penetrate the Paleozoic aquifer.

A plot of calibrated versus observed head values from the Case 1 conceptual model is shown in Figure 3-3. The mean calibration error of -0.01 m [-0.03 ft] is quite small, which indicates errors in calculated head values are evenly distributed above and below the zero error line in Figure 3-3. The mean absolute error for the 70 observation points is 9.6 m [31 ft], and the root-mean-square error is 17.3 m [56.9 ft]. This calibration error is somewhat less than the root-mean-square error of 30 m [98 ft] reported by DOE for its calibrated site-scale saturated flow model, which covers a similar model domain (CRWMS M&O, 2000a). In general, calibration errors are smallest in the area of greatest interest, hydraulically downgradient from Yucca Mountain, east and south of the proposed repository location. It should be recognized that a relatively small error in calculated hydraulic head at any particular location can produce a more significant error in the local hydraulic gradient. It is, therefore, not advisable to use model results to make small-scale (e.g., cell to cell) inferences about groundwater fluxes and flow directions. If, however, model calibration errors throughout the model domain are evenly distributed among positive and negative values, such that the mean calibration error is near zero, then it can be inferred that, at larger scales, local errors in calculated groundwater gradients would be offsetting and that the calculated groundwater fluxes and flow directions at larger scales can be considered reasonably accurate.

Larger calibration errors, on the order of 10–50 m [30–160 ft], generally occur for observation points near structural features that produce steep hydraulic gradients. Many of these residual errors are attributable to coarse grid discretization and are not considered problematic. For example, across the Solitario Canyon fault (SC–IR in Table 2-1), hydraulic heads change by tens of meters within a lateral distance of one grid cell. Large calibration errors occur in such areas because calculated heads represent grid-cell centers, and it is not possible to consistently and precisely locate grid cells with respect to the observation points. Such residual errors could be reduced by grid refinement or by widening fault zones so head changes do not occur so abruptly.

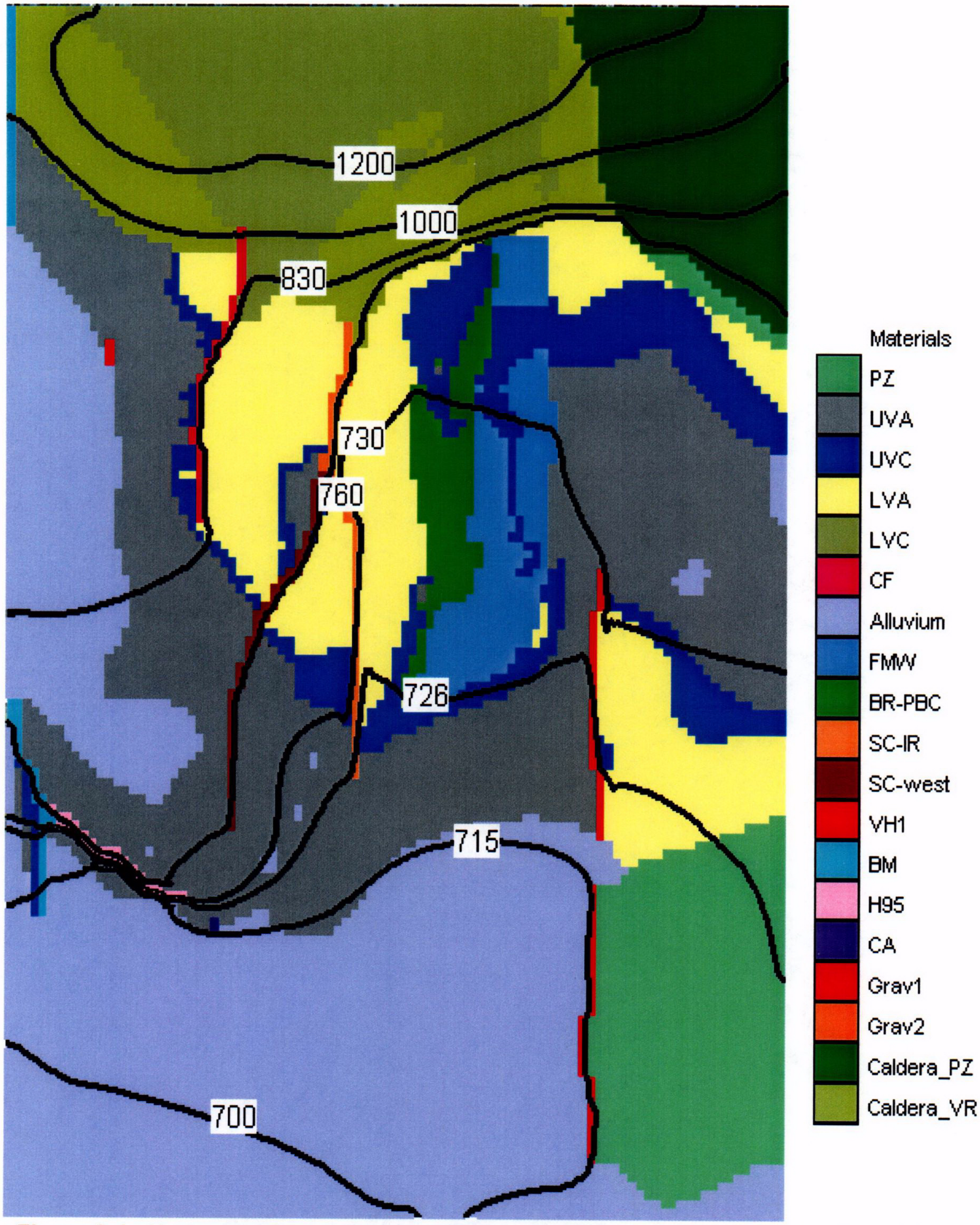

Figure 3-1. Horizontal Cross Section of Model Layer 7 Showing Hydrostratigraphic and Structural Material Types and Calculated Steady-State Hydraulic Head Contours for Case 1 (Contour Units Are Meters Above Mean Sea Level for Conversion to Feet 1 m = 3.281 ft). Model Scale and Repository Location Are Shown in Figure 2-1.

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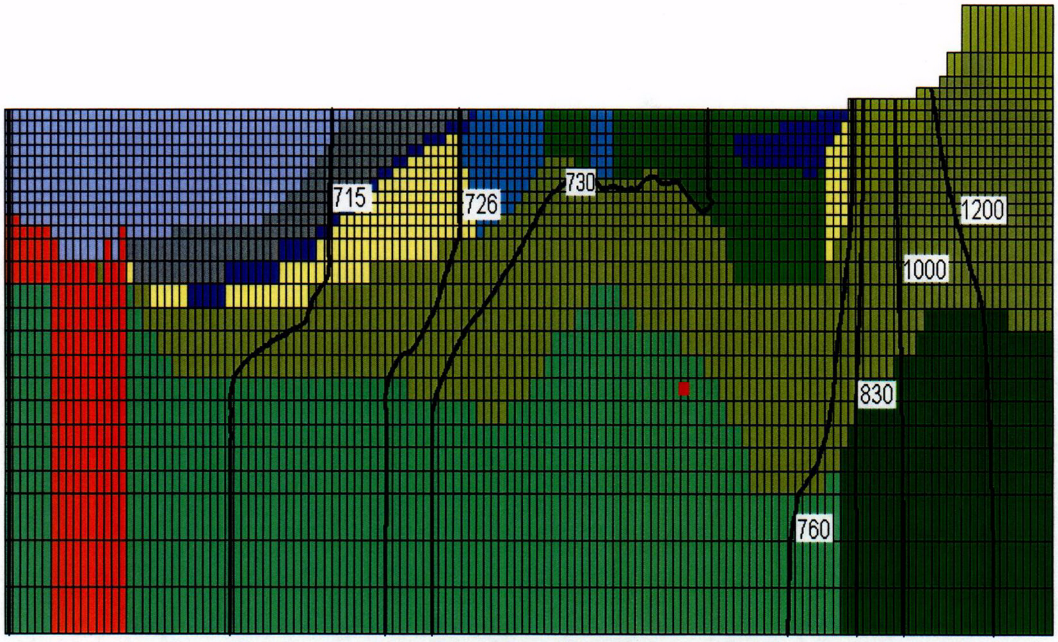

Figure 3-2. Vertical Cross Section (Looking West) through Center of Model Domain, Showing Hydrostratigraphic and Structural Material Types (See Figure 3-1 for Materials Legend) and Calculated Steady-State Hydraulic Head Contour Lines for the Case 1 Model (Contour Units Are Meters Above Sea Level). Well UE–25 p#1 Observation Point Is Indicated by the Red Square. Horizontal Model Scale Is Shown in Figure 2-1; Vertical Scale Is 2,700 m [8,860 ft].

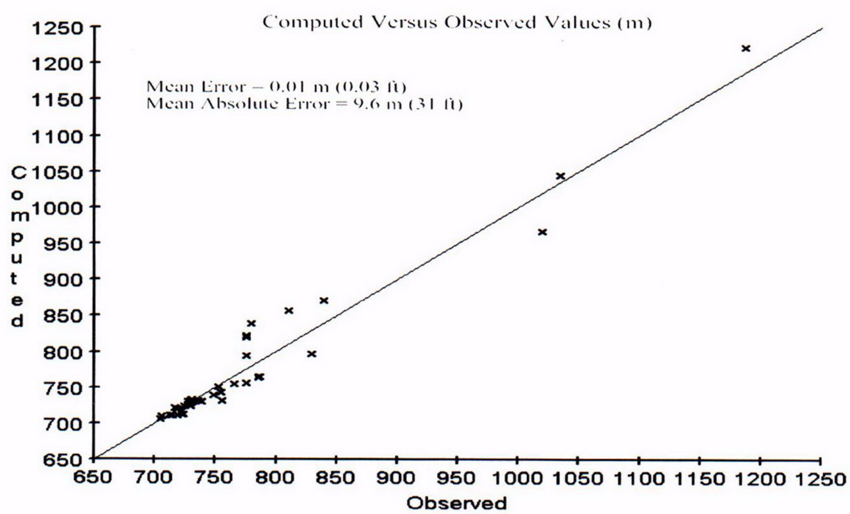

Figure 3-3. Plot of Computed Versus Observed Hydraulic Head Values for the Case 1 Steady-State Model Calibration

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Figure 3-4 shows MODPATH-calculated flow trajectories for Case 1. Starting locations for 80 particles were assigned to the uppermost active model cells beneath the approximate footprint of the proposed repository. Most of the simulated particles travel east-southeast for a relatively short distance of 1–2 km [0.6–1.2 mi] before turning abruptly south and continuing southward to the 18-km [11-mi] compliance boundary where particle trajectory calculations were stopped. The locations where the particles turn south coincide with the western edge of the modeled Bow Ridge–Paintbrush Canyon fault zone (BR–PBC in Table 2-1). Apparently, as soon as the particles reach this zone of increased permeability, they are swept along the edge of the zone for long distances and do not penetrate farther eastward. This process results in a narrow swath of particles with little lateral spreading. The view of the modeled flow paths in Figure 3-5 shows that, for this case, with no recharge occurring at the proposed repository location, the flow paths generally remain within 50 m [160 ft] of the modeled water table surface. Although particles appear to be started above the water table in Figure 3-5, this is an artifact of projecting the three-dimensional model onto the two-dimensional cross section.

Figure 3-6 shows that the distribution of $\log_{10}$ particle travel times to the compliance boundary spans two orders of magnitude and is somewhat bimodal. The minimum particle travel time for the Case 1 simulation was 400 years, and maximum travel time was 51,200 years. Average travel time was 17,000 years; 65 percent of particles had travel times less than the average. Approximately half the particles arrive at the compliance boundary within a few thousand years. The rate of particle arrivals diminishes until about 10,000 years and reaches another peak at approximately 30,000 years. The earlier arrival times generally represent particles released from the southern half of the repository, which stay mostly within volcanic tuffs units conceptualized as having flow mainly in fractures. These tuff units are assigned a low porosity value of 0.001 (e.g., LVA and BR–PBC in Table 2-1). Longer travel times generally represent particles released in the northern half of the repository footprint that travel greater distances through the upper volcanic confining unit (UVC in Table 2-1), which is assigned a high porosity value of 0.1 to represent a conceptualization of predominant matrix flow.

The next section presents the Case 2 model, which explores whether the inclusion of the relatively minor amount of recharge at the proposed repository location can significantly affect calculated flow paths and groundwater travel times.

3.2 Case 2 Model

The Case 2 model is identical to the Case 1 model in every respect except that a recharge rate of 5 mm/yr [0.2 in/yr] is applied to the area of the proposed repository. This additional recharge area is represented by the yellow shaded zone in Figure 2-2(a). The 5 mm/yr [0.2 in/yr] recharge rate is consistent with estimates of present-day recharge over the repository area (CRWMS M&O, 2000b). Although this recharge flux is rather minuscule compared to lateral cell to cell flux rates beneath Yucca Mountain, comparison of the Case 1 and Case 2 models permits an assessment of whether such small influxes are important for calculating groundwater flow paths and travel times.

Hydraulic head contour maps and calibration error plots for the Case 2 model are not shown because they are barely distinguishable from those shown in Figures 3-1, 3-2, and 3-3 for the Case 1 model. Mean absolute calibration error for the Case 2 model increased by less than 1 percent from that of the Case 1 model, which indicates the recharge in the repository area does not significantly affect model calibration error. The mean error, however, did increase from

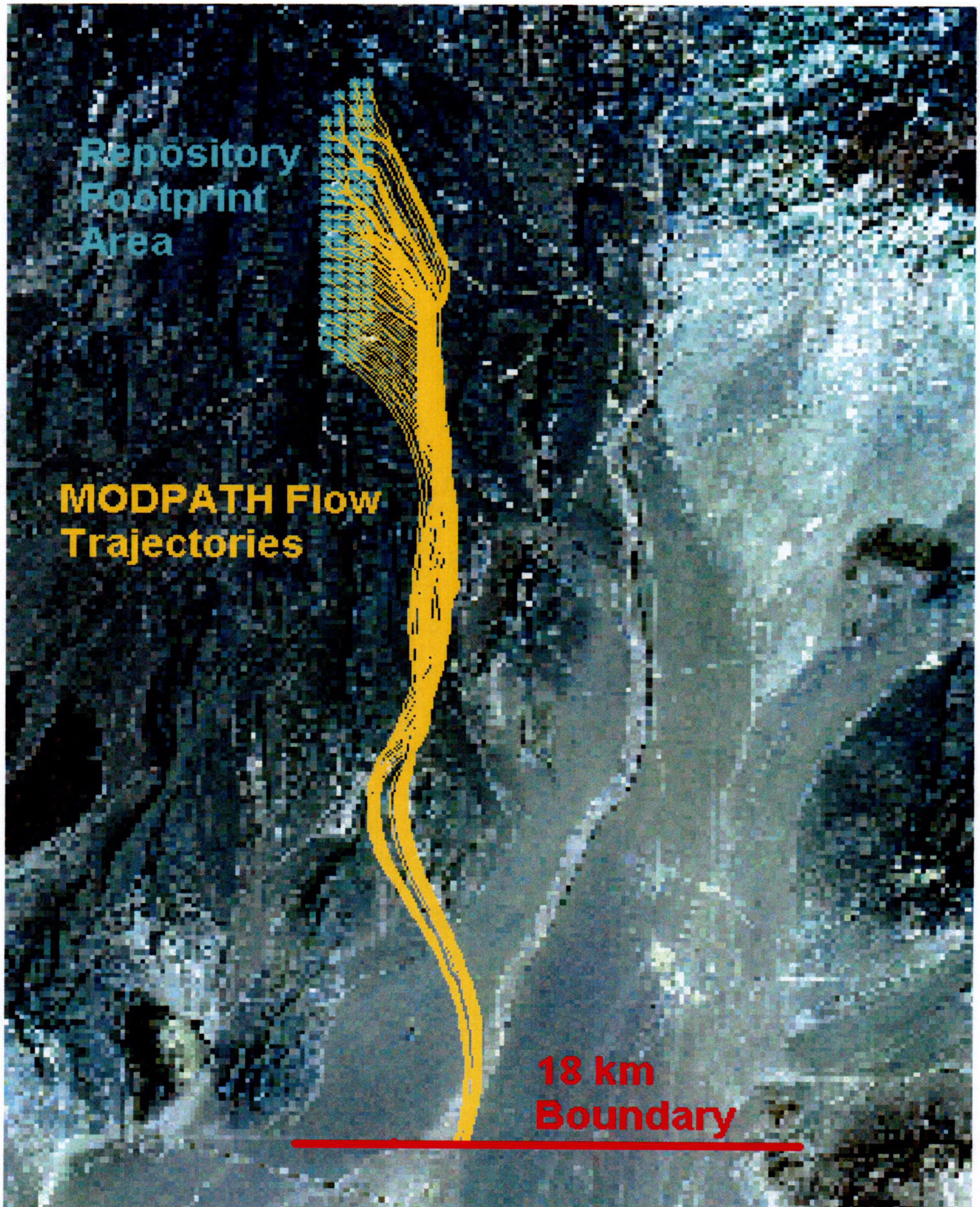

Figure 3-4. Modeled Flow Trajectories from the Approximate Footprint of the Proposed Repository to the 18-km [11-mi] Compliance Boundary in the South for the Case 1 Model with No Recharge Below the Repository Footprint Area

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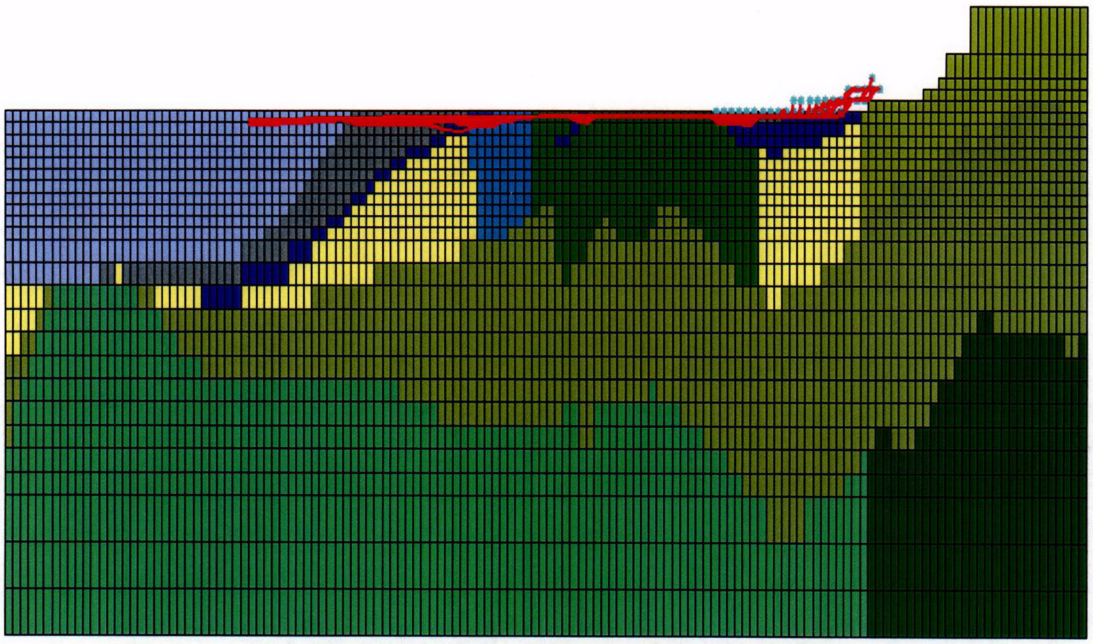

Figure 3-5. Vertical Profile (Looking West) through Center of Model Domain, Showing Calculated Flow Trajectories (Red Lines) for the Case 1 Model. Model Scale Is Shown in Figure 2-1.

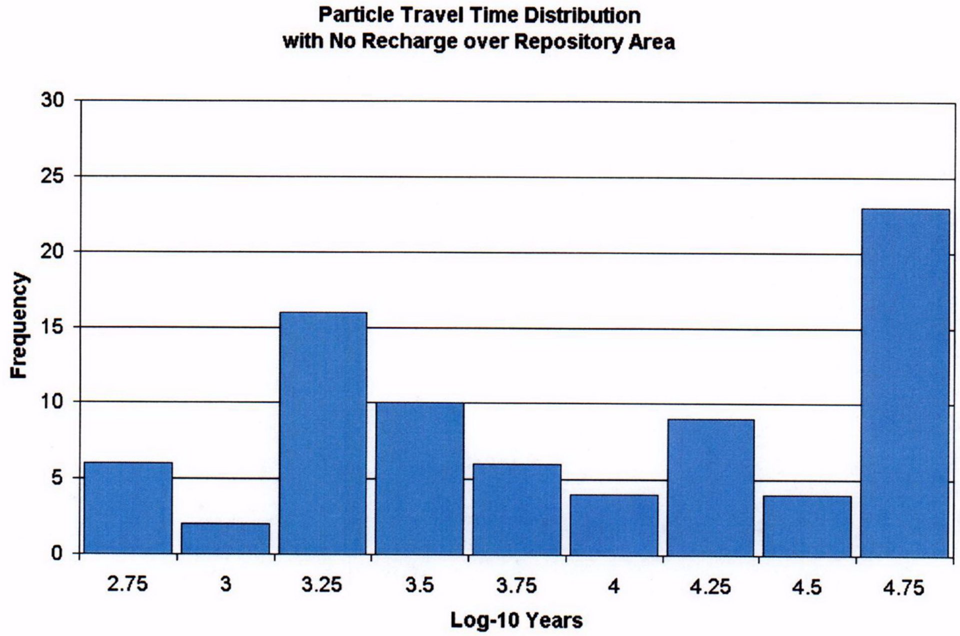

Figure 3-6. Histogram Showing Particle Travel Time Distribution for the Case 1 Model with No Recharge Applied to the Area of the Proposed Repository

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nearly 0 to 1.4 m [4.6 ft], which indicates a small bias toward positive error values, but is not considered significant for the purpose of this investigation.

Figure 3-7 shows the MODPATH-calculated flow trajectories for the Case 2 model in plan view. These calculated flow paths are similar to those of the Case 1 model, but particles travel slightly farther east before turning due south. The Case 2 flow trajectories also reach the compliance boundary at essentially the same place as in Case 1, but project a swath nearly twice as wide.

The vertical profile of the Case 2 flow trajectories, shown in Figure 3-8, is strikingly different from Case 1. Apparently, 5 mm/yr [0.2 in/yr] recharge in the repository area, while quite small compared to lateral groundwater flux in this area, provides enough of a downward flow gradient to drive flow paths to depths exceeding 500 m [1,600 ft] below the water table. Figure 3-8 also shows the flow trajectories of these deeper flow paths tend to follow the topography of the underlying lower volcanic confining unit, which increases the total distance traveled in the volcanic tuff units.

The distribution of calculated groundwater travel times for Case 2, shown in Figure 3-9, is also markedly different from the Case 1 results. The minimum particle travel time for Case 2 was 357 years; the maximum particle travel time was 2,299 years. The average particle travel time for Case 2 was only 950 years, and 57.5 percent of particles had travel times less than the average. Interestingly, despite the somewhat longer flow paths for Case 2, the average groundwater travel time is more than one order of magnitude less than the average travel time for Case 1. This substantial reduction in calculated travel times is mainly attributable to the change in flow paths of particles originating in the northern repository area. Recall that, for the Case 1 model, particles in the northern repository area remained near the water table and traveled significant distances through the upper volcanic confining unit, which is assigned a high porosity value of 0.1. Conversely, in the Case 2 model, the deeper flow paths cause the particles from the northern repository area to flow beneath and almost completely bypass the volcanic confining unit, remaining in the lower volcanic aquifer and Bow Ridge–Paintbrush Canyon fault zone, which are assigned a low porosity value of 0.001. Note that Figure 3-8 can be somewhat deceiving because it is a two-dimensional projection of three-dimensional flow paths. Although particles from the northern repository area appear to pass through the upper volcanic confining (dark blue) unit, most particles are actually traveling downward and beneath the upper volcanic confining unit to the west of this unit.

The significant difference in predicted groundwater travel times between the Case 1 and Case 2 models is largely a result of the conceptualizations that matrix flow is dominant in the upper volcanic confining unit, and that fracture flow is dominant in the lower volcanic aquifer and Bow Ridge–Paintbrush Canyon fault zone. The difference in porosity values assigned to these units is the main reason for the different travel time estimates. With this caveat in mind, the results of the Case 2 modeling study, when compared with Case 1, suggest it is important to consider the relatively small amount of recharge in the repository area when evaluating potential saturated zone flow paths and groundwater travel times. This conclusion leads to the question whether it is important to consider even greater recharge rates that might occur as a result of climate change. This question is explored in the Case 3 modeling study presented in the following section.

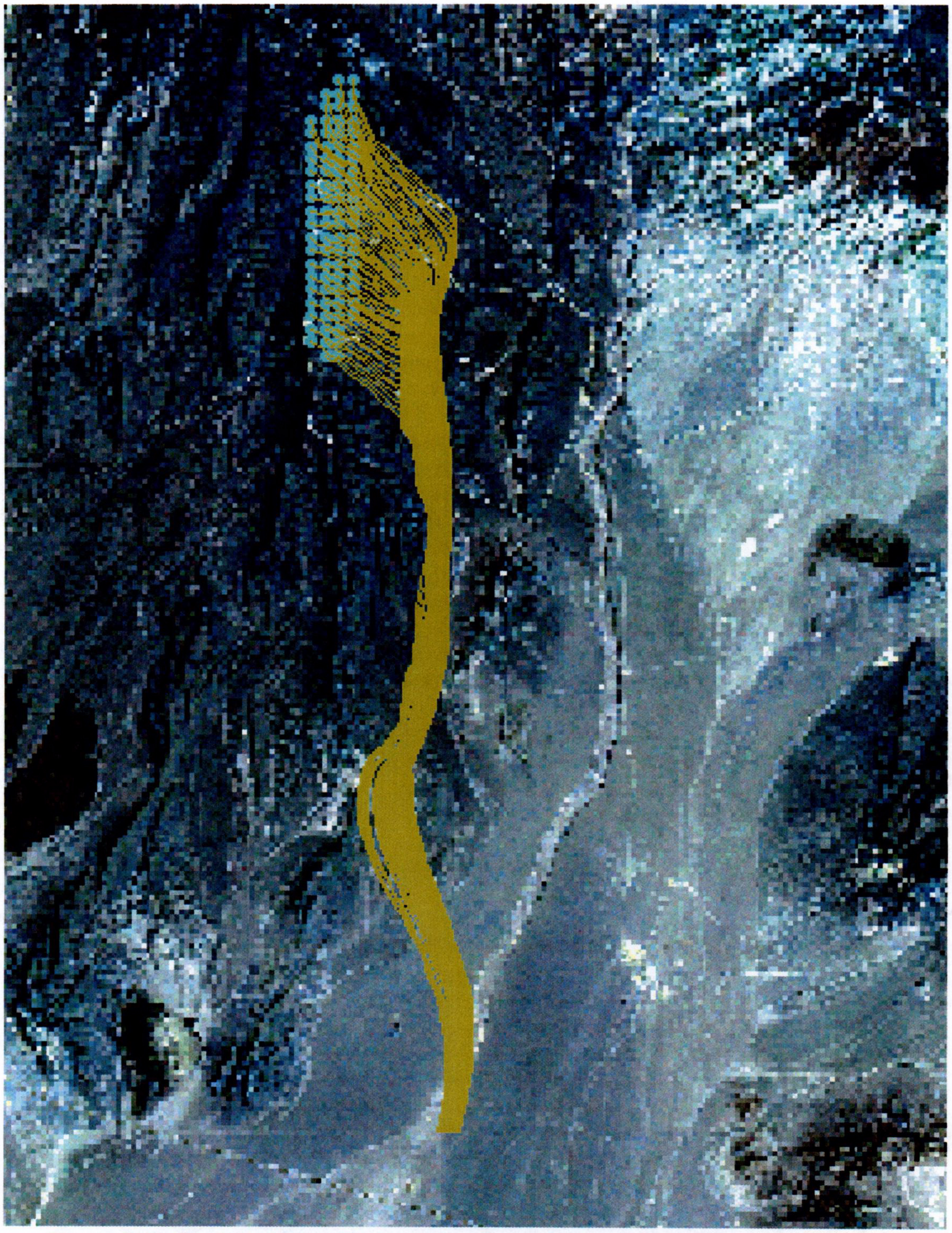

Figure 3-7. Modeled Flow Trajectories from the Approximate Footprint of the Proposed Repository to the 18-km [11-mi] Compliance Boundary in the South for the Case 2 Model, Which Includes Recharge in the Repository Footprint Area

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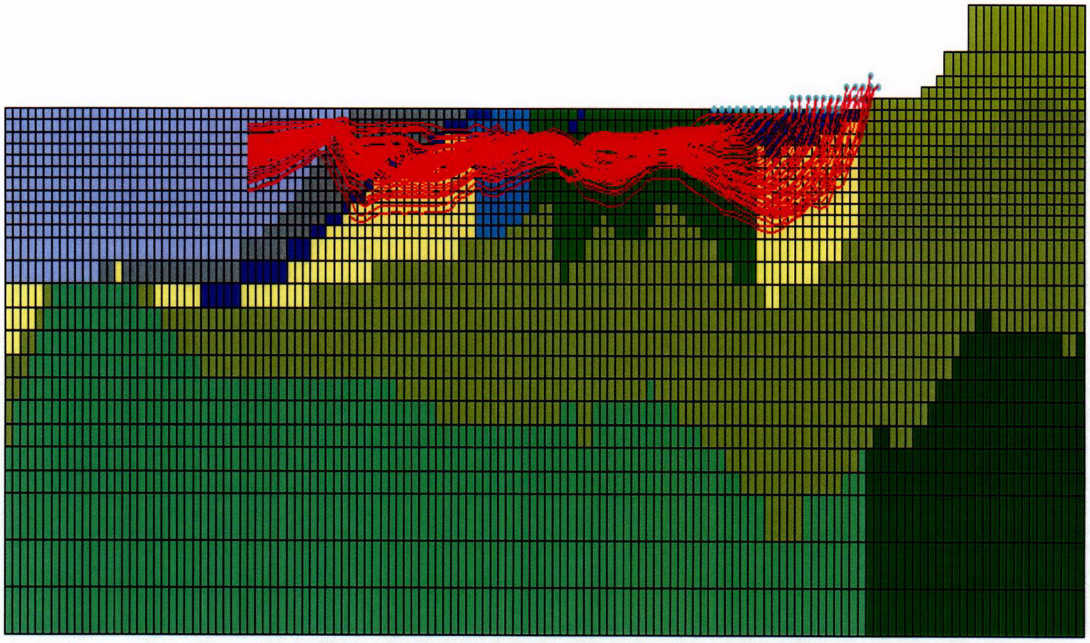

Figure 3-8. Vertical Profile (Looking West) through Center of Model Domain, Showing Calculated Flow Trajectories (Red Lines) for the Case 2 Model. Model Scale Is Shown in Figure 2-2. (Compare to Figure 3-5)

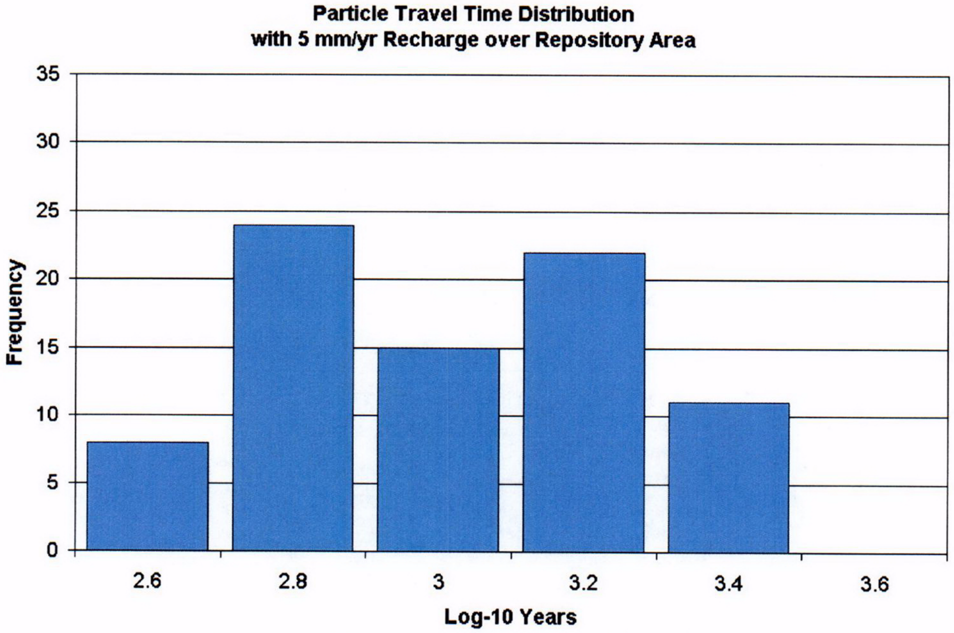

Figure 3-9. Histogram Showing Particle Travel Time Distribution for the Case 2 Model with 5 mm/yr [0.2 in/yr] Recharge Applied to the Area of the Proposed Repository

C08

3.3 Case 3 Model

The Case 3 model is intended to evaluate potential effects on flow paths of increased recharge and water table elevation that might follow a future shift to wetter climate conditions. The DOE saturated flow model (CRWMS M&O, 2000a) used to predict flow paths for the Site Recommendation was calibrated to present-day climate conditions; hence, flow paths for expected wetter climate conditions were not explicitly considered. DOE indicated, however, the version of the saturated flow model used to support a License Application will include the effects of water table rise (Bechtel SAIC Company, LLC, 2002). Hence, the modeling results for Case 3 provide NRC and CNWRA staffs with an enhanced perspective for review of the revised DOE approach.

For the Case 3 modeling study, recharge rates were doubled from the Case 2 model, and constant-head values at the model side boundaries were increased by 5 percent. A percentage change in head values was used instead of a constant magnitude change because the percentage approach results in greater increases in boundary heads in the northern model area where regional recharge occurs in the mountains north of the model domain. The 5-percent increase in boundary head values was established through trial and error to find the amount just sufficient to raise the water table to the elevation of the ground surface at the location of Well NC–EWDP–9S [see Figure 2-2(a)]. The presence of paleo-spring evaporite deposits near Well NC–EWDP–9S suggests the water table elevation has risen to the surface level at this location in the past. The MODFLOW Drain package was used to assign a single drain cell at this model location to simulate effects of spring seepage whenever the calculated water table elevation exceeds the drain elevation of 795 m [2,600 ft] above sea level. A moderately high conductance value of 300 m^2/d [3,200 ft^2/d] was arbitrarily assigned to the drain cell. The resulting steady-state solution to the Case 3 model produced a calculated drain seepage of 0.3 m^3/d [11 ft^3/d] at the NC–EWDP–9S well location and a calculated boundary head value only 2 mm [0.08 in] above the drain elevation.

Figure 3-10 shows MODPATH-calculated flow trajectories for the Case 3 model in plan view. These calculated flow paths are similar to those of the Case 2 model, but cover a slightly wider swath. The vertical profile of the Case 3 flow trajectories, shown in Figure 3-11, is hardly discernable from the profile for the Case 2 model, but a few of the flow trajectories travel slightly deeper.

The distribution of $\log_{10}$ particle travel times calculated for Case 3 is shown in Figure 3-12. Minimum particle travel time was 330 years, and maximum travel time was 4,200 years. The average particle travel time was 800 years, and 56 percent of particles had travel times less than the average. A comparison of Figures 3-9 and 3-12 shows that the distribution of particle travel times for Case 3 is not drastically different from Case 2.

The maximum travel time for Case 3 (represented by a single particle in Figure 3-12) is attributed to a particle originating from the northernmost edge of the repository footprint where the water table rise is greatest. The raised water table requires the particle to travel farther downward through a low-permeability zone (Caldera_VR in Table 2-1). Hence, it appears the magnitude of water table rise under the northern repository area may have some effect on calculated saturated zone groundwater travel times. Increases in saturated zone travel times in areas of greater water table rise would, however, probably be offset by an accompanying decrease in unsaturated zone travel time from the repository to the water table.

Figure 3-10. Modeled Flow Trajectories from the Approximate Footprint of the Proposed Repository to the 18-km [11-mi] Compliance Boundary in the South for the Case 3 Model, Which Includes Twice the Recharge of the Case 2 Model and an Elevated Water Table (Compare to Figure 3-7)

C09

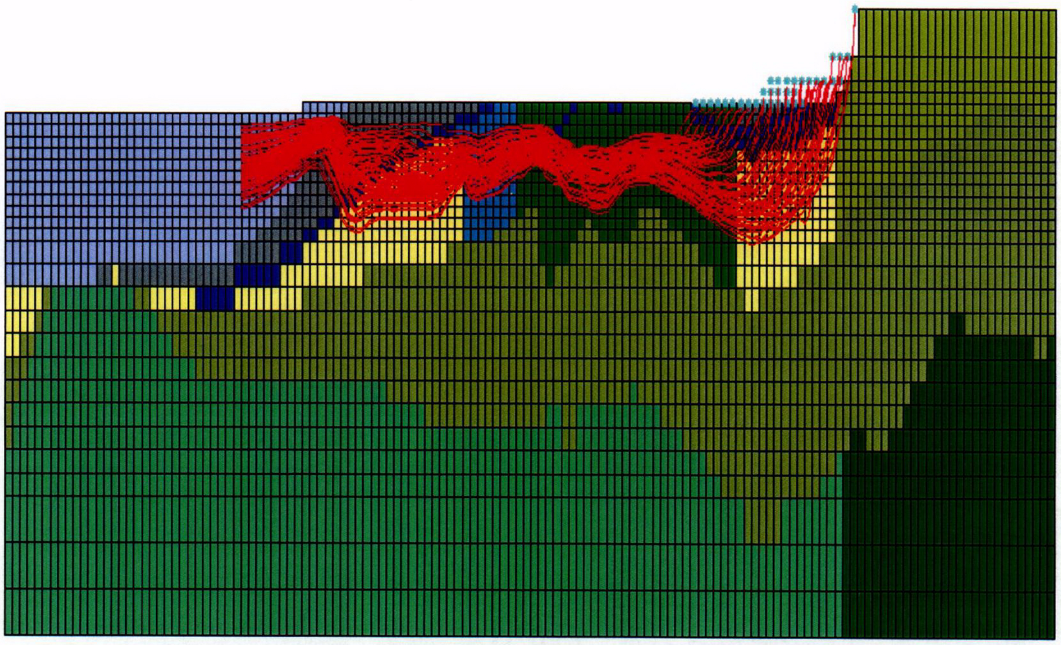

Figure 3-11. Vertical Profile (Looking West) through Center of Model Domain, Showing Calculated Flow Trajectories (Red Lines) for the Case 3 Model. Model Scale Is Shown in Figure 2-1.

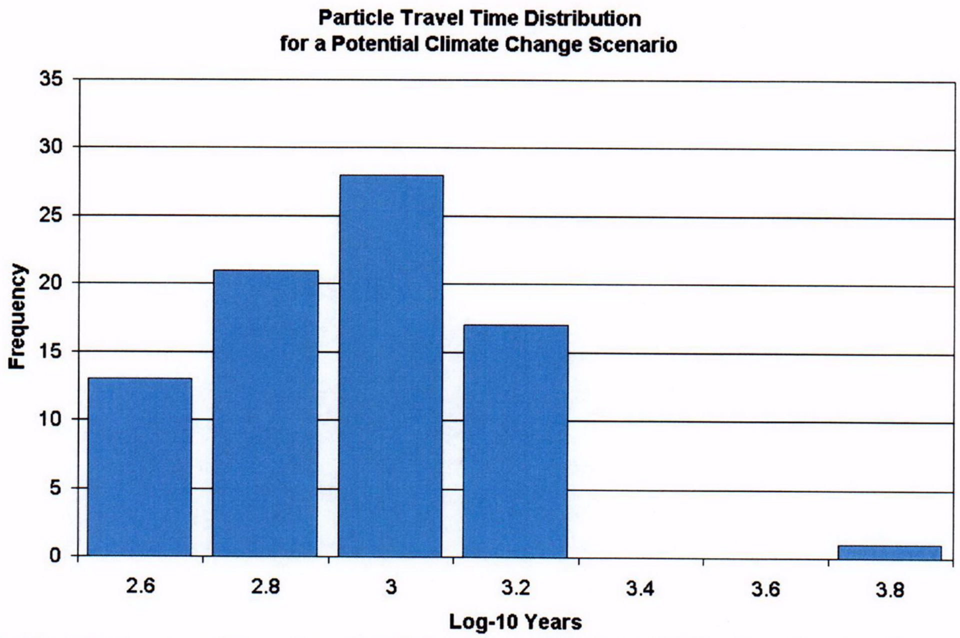

Figure 3-12. Histogram Showing Particle Travel Time Distribution for the Case 3 Model with Twice the Recharge of the Case 2 Model and Increased Water Table Elevation (Compare to Figure 3-9)

C10

Additional discussion of the potential magnitude of water table rise is provided in the following section describing the Case 4 modeling study, which evaluates effects of increased recharge from the Fortymile Wash area that may occur during wetter future climate conditions.

3.4 Case 4 Model

The Case 4 model is identical to the Case 3 model with the exception that a recharge rate of 200 mm/yr [8 in/yr] is applied to the Fortymile Wash channel area indicated in Figure 2-2(b). During present-day, arid climate conditions, stream flows in Fortymile Wash occur infrequently following large storm events, typically separated by periods of several years or even decades. In future, wetter climate conditions, stream flows in Fortymile Wash could be more frequent and could supply a significant source of groundwater recharge. Although actual recharge to the wash channel in future climate conditions has not been evaluated, this analysis provides some indication as to whether a large increase in wash channel recharge is important to predicted flow paths and groundwater travel times.

Figure 3-13 shows the MODPATH-calculated flow trajectories for the Case 4 model in plan view. The Case 4 flow paths are similar to those of the Case 3 model, but reach the compliance boundary slightly farther to the west and project a slightly narrower swath. The vertical depth profile for the Case 4 flow paths is not significantly different from those of the Case 2 and Case 3 models (see Figures 3-8 and 3-11) and, hence, is not shown.

The distribution of calculated groundwater travel times for Case 4, shown in Figure 3-14, is also similar to the Case 3 results. Minimum particle travel time was 278 years, and maximum particle travel time was 4,415 years. Average particle travel time was 728 years, and 62 percent of particles had travel times less than the average. The Case 4 model results suggest the inclusion of recharge in the Fortymile Wash channel does not have a substantial effect on either the modeled flow paths or groundwater travel times.

The Case 4 model was also used to evaluate the potential magnitude of water table rise during future wetter climate conditions. Figure 3-15 is a shaded contour map of the model area that shows differences in calculated steady-state water table elevations between the Case 2 and the Case 4 models. Recall that a key constraint placed on the boundary conditions for the Case 3 and Case 4 models was to produce just enough water table rise to initiate spring seepage at the location of Well NC–EWDP–9S. Using this constraint and the Case 4 set of modeling assumptions, calculated water table rise in the area of the proposed repository is in the range of 50–150 m [160–500 ft]. This rise generally is consistent with the assumed 120 m [390 ft] water table rise used in the DOE abstraction of unsaturated zone transport used for total system performance assessment of the proposed repository (CRWMS M&O, 2000b).

Experience gained from initial trial model runs indicated the calculated amount of water table rise is highly sensitive to the ratio of the applied recharge rate to the hydraulic conductivity of the uppermost material types. Accordingly, the greatest projected water table rise for this model scenario occurs in the northern model area where recharge is applied above material types with low permeability. In fact, an attempt to run a model with a constant 50 mm/yr [2 in/yr] recharge in the northern model area produced calculated hydraulic heads much higher than the ground surface elevations in many areas. Such high hydraulic heads would not be physically realistic, even though a recharge rate of greater than 50 mm/yr [2 in/yr] is certainly plausible at the ground surface in this area of the model [e.g., see recharge estimates by

Figure 3-13. Modeled Flow Trajectories from the Approximate Footprint of the Proposed Repository to the 18-km [11-mi] Compliance Boundary in the South for the Case 4 Model, Which Includes 200 mm/yr [8 in/yr] Recharge in Fortymile Wash, but Is Otherwise the Same As the Case 3 Model (Compare to Figure 3-7)

C11

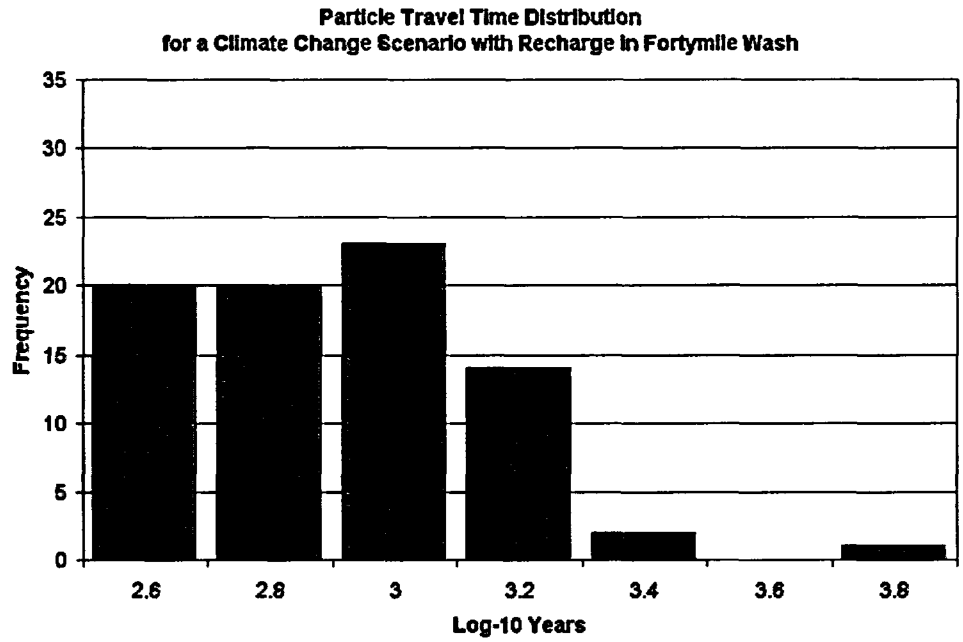

Figure 3-14. Histogram Showing Particle Travel Time Distribution for the Case 4 Model, Which Is the Same As the Case 3 Model with the Addition of 200 mm/yr [8 in/yr] Recharge in Fortymile Wash (Compare to Figure 3-9)

Flint, et al. (2000)]. Future modeling work can be performed to evaluate whether differing conceptualizations of recharge rates and hydrologic properties in the northern model area could have important implications for the calculation of flow paths or groundwater travel times. The limited evaluation presented in this report, however, suggests the amount of water table rise in the northern model area may not strongly affect groundwater flow paths or travel times from the proposed repository location.

3.5 Summary and Discussion

The following four conclusions can be drawn from the modeling case studies presented in this report:

- A small recharge rate {5 mm/yr [0.2 in/yr]} in the area of the proposed repository has a substantial effect on calculated flow trajectories and, depending on conceptualizations of fracture or matrix flow for hydrostratigraphic units, may also profoundly affect groundwater travel time calculations. For the porosity values assumed in this report, recharge in the repository area resulted in an order of magnitude in calculated mean groundwater travel time from Yucca Mountain to the regulatory compliance boundary.

- Further increases in recharge rates in the repository area and in the model area north of Yucca Mountain do not have a substantial effect of flow trajectory or groundwater travel time calculations.

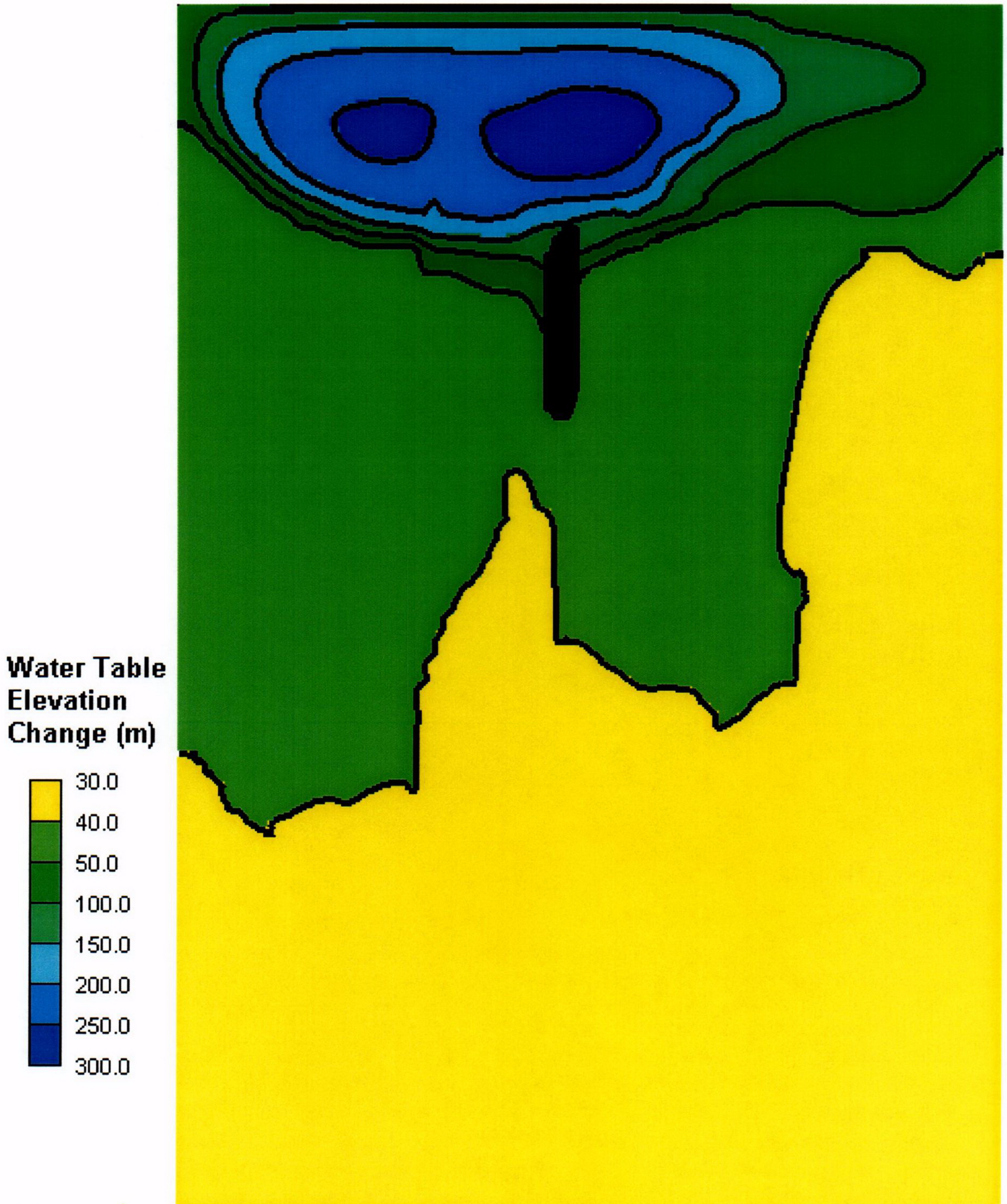

Figure 3-15. Plan View Map of Model Area Showing Difference in Steady-State Water Table Elevations Between the Case 2 and Case 4 Models. Model Area Scale Is Shown in Figure 2-1. The Approximate Footprint of the Proposed Repository Area Is Shaded in Black. Model Area Scale is Shown in Figure 2-1. Note, Information Presented in Meters; for Conversion to Feet, use 1 m = 3.281 ft.

C12

- The water table elevation in the northern model area is sensitive to the imposed recharge rate, however, groundwater flow trajectories and travel times from the proposed repository area were not strongly affected (by the rather large water table rise considered in th Cases 3 and 4 modeling studies) by the water table position in that area.

- Recharge in the Fortymile Wash area did not significantly affect calculated flow trajectories and groundwater travel times, given the set of calibrated hydrologic properties used in this modeling study.

A previous modeling study by Winterle, et al. (2003) showed that different interpretations of hydrostratigraphic and structural features can produce reasonable model calibrations, yet result in significantly different calculations of flow paths and groundwater travel time distributions. It is not clear if all conclusions reached for the modeling studies presented here would apply to an alternative hydrogeologic interpretation and set of hydrologic property values. For example, an alternative model calibration presented by Winterle, et al. (2003) produced flow paths that traveled much farther east, almost reaching the area beneath the Fortymile Wash channel. Inclusion of recharge to the Fortymile Wash area for that alternative model could have had a more significant effect on modeled flow paths than was found in this modeling study. Hence, CNWRA staff will continue to use the independent site-scale saturated zone flow model to gain improved insight into potential model uncertainties that could prove important to saturated zone flow paths from Yucca Mountain.

Another goal for developing the CNWRA saturated zone flow model (Winterle, et al., 2002) was to use the model to develop or improve the abstraction of saturated zone flow and transport in the independent Total-system Performance Assessment (TPA) Version 4.0 code (Mohanty, et al., 2000) used by the NRC and CNWRA staffs. The current TPA Version 4.0 code abstraction uses a one-dimensional stream tube approach. The geometries of the flow and transport stream tubes were estimated using a simple two-dimensional, flow-net analysis based on an assumption of isotropic flow along a hydraulic gradient inferred from the present-day slope of the water table near Yucca Mountain. Flow paths inferred from the results of the model studies presented in this report would provide a much improved technical basis for the abstraction of saturated zone flow and transport for the updated TPA Version 5.0 code currently being developed. Specifically, the specified geometries of the one-dimensional stream tubes can be revised to be consistent with potential flow paths calculated from the three-dimensional site-scale saturated zone flow model. Because most of the 10,000-year compliance period for repository performance is assumed to be affected by wetter climate conditions and increased recharge, the Case 4 modeling study presented in this report would provide a reasonable basecase scenario for future calculations. Other stream tube geometries that may be determined from future site-scale flow modeling activities, if found to differ significantly from the Case 4 study, also could be abstracted to evaluate potential effects of alternative flow model conceptualizations on repository performance.

4 CONCLUSION

The CNWRA three-dimensional groundwater flow model provides a useful tool to evaluate the effects of conceptual model uncertainty on calculations of saturated zone flow paths, groundwater travel times, and potential magnitudes of water table rise during future climate conditions.

Four modeling case studies presented in this report indicate recharge over the potential repository area strongly affects groundwater travel times. Increased recharge and water table rise that may accompany a future wetter climate and the addition of recharge in the Fortymile Wash area did not substantially affect flow path or travel time calculations in the case studies presented in this report, however, the effects of these processes should be evaluated for alternative hydrogeologic interpretations. The Case 4 modeling study presented here would provide a reasonable basecase scenario for the abstraction of saturated zone flow and transport in performance assessments using the TPA code.

5 REFERENCES

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